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Ocean acidification impacts in select Pacific Basin coral reef ecosystems

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ABSTRACT

In the vast tropical Pacific Basin islands, corals reef ecosystems are one of the defining marine habitats, critical for maintaining biodiversity and supporting highly productive fisheries. These reefs are also vital for tourism and armoring exposed shorelines against erosion and other storm-related effects. Since the 1980's, there has been growing evidence that these Pacific Basin coral reef ecosystems are highly vulnerable to the combined effects of both climatic and non-climatic stressors. Observations of widespread bleaching in the region has been linked to acute temperature stress, and the heightened recurrence intervals and intensity of storms has been correlated to recent climate-change induced impacts. Ocean acidification is another ubiquitous stressor with dramatic consequences to biological systems. In this paper we describe what sets this region apart from other coral reef regions around the world, and highlight some examples of the diverse response to ocean acidification threats and associated socio-economic impacts.

Contents

1. Introduction

Coral reefs occur in many tropical and inter-tropical regions across the globe, providing a range of ecosystem services and functions. While coral reefs harbor the highest biodiversity of any ecosystem and directly support over 500 million people worldwide, they are also among the most threatened due to unprecedented impacts of climate change and ocean acidification, combined with growing local pressures (Wilkinson, 2004). The impacts of climate change, ocean acidification and coastal development on coral reef ecosystems vary across regional to highly local scales. As such, the present paper explores how Pacific Basin coral reef ecosystems experience and respond to the impacts of climate change and ocean acidification.

Globally, the ocean absorbs roughly one third of the CO_2 molecules emitted into the atmosphere by natural and human activities (Doney et al., 2009). The 'cost' of this marine CO_2 sequestration results in a systematic and rapid increase in seawater acidity. This decline in ocean pH – about 30% since pre-industrial

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times – is now occurring a rate ten times faster than has been observed during the past 300 million years (Hönisch et al., 2012). At the current rate of CO_2 emissions, the acidity of the surface ocean is expected to increase 150% over pre-industrial levels by the end of this century (Orr et al., 2005; Feely et al., 2009). Indeed, atmospheric and open-ocean time series observations clearly show the relationship between atmospheric CO_2 levels, pCO_2, and seawater pH over the past 3 decades.

Why is ocean acidification such a concern? As CO_2 dissolves in seawater, it readily forms carbonic $[H_2CO_3]$ acid, which can react to form free hydrogen ions $[H^+]$ and bicarbonate $[HCOHCO_3^-]$. Seawater is naturally saturated with carbonate $[COCO_3^{2-}]$ that can combine with $[H^+]$ to form more bicarbonate ions. As this carbonate becomes depleted over time, seawater can become undersaturated with respect to important calcium carbonate minerals that are fundamental building blocks for many important marine species, such as corals, zooplankton, and shellfish (Orr et al., 2005). Reef building requires that organisms sequester $CaCO_3$ at a rate faster than physical-, biological-, and chemical-erosion, and a projected continued decrease in $CaCO_3$ production over time will likely pose a significant deficit for many coral reefs.

Ocean acidification impacts on marine ecosystems and their biota are manifested in various complex ways that are compounded by other climate-change induced stressors, such as ocean warming, deoxygenation, and pollution (Leal et al., 2018; Riebesell and Gattuso, 2015). The health of coral reef ecosystems has identifiable impacts on local economies as well as social and cultural well-being, particularly in under-resourced and developing countries. Economic impacts resulting from reef degradation include less tourism, declines in local fish catch, and damaged infrastructure due to higher vulnerability to storms, waves, and erosion (Hoegh-Guldberg et al., 2007).

Ocean acidification is a global phenomenon; however, its impacts are often expressed at the local level. The present paper discusses the stressors and impacts on select coral reef ecosystems in the Pacific Basin, the potential economic costs to coastal communities, proposed solutions to mitigate these environmental impacts, and the range of actions being implemented.

2. Status of select Pacific Basin coral reef ecosystems

The Pacific Basin consists of more than 20,000 islands crossing large latitudinal and longitudinal gradients, featuring tropical and subtropical climates, and which support significant cultural diversity and biodiversity. These islands are further heterogeneous in their governance structures, levels of development, and population density, presenting challenges to finding uniform solutions to ocean acidification across all sites. This socio-economic and ecological heterogeneity also presents an opportunity for regional solutions testing. To capture the variation in impacts and responses to ocean acidification on coral reefs in this region, five Pacific Basin coral reef ecosystems were identified as case studies (Fig. 1).

While every reef type is represented throughout the Pacific Basin, the extent to which local economies depend on these ecosystem services varies. Large gaps remain in quantifying the economic valuation of coral reef ecosystems to human communities (Table 1). Nonetheless, every island shares a similar vulnerability to ocean acidification, climate change and sea level rise, a reliance on fisheries for local consumption and export earnings, and an economic and cultural reliance on coral reef ecosystem services, such as coastal protection and recreational activities. These similarities, and differences, can provide insight on how different social, institutional, and environmental factors contribute to different levels of coral reef resilience to ocean acidification.

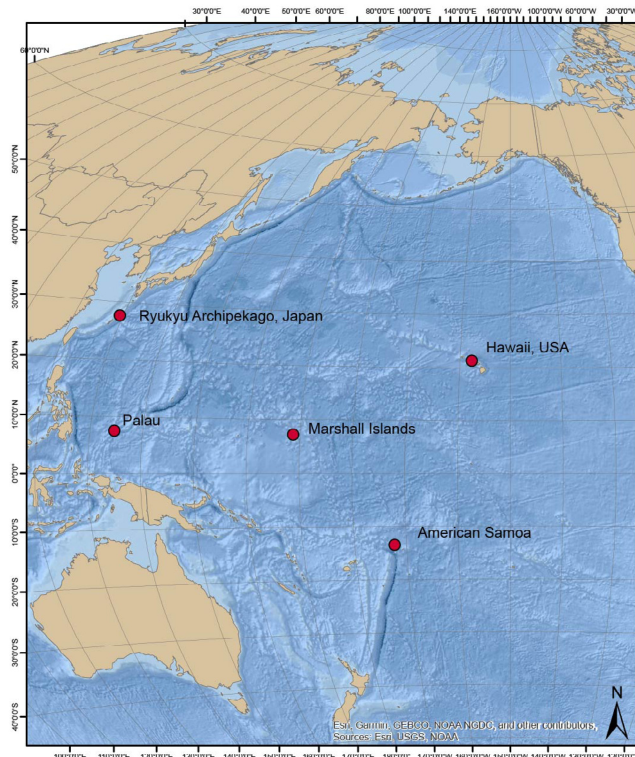

Fig. 1. The Pacific Islands coral reef ecosystems highlighted in this map were chosen as case studies during the 4th International Workshop "Bridging the Gap between Ocean Acidification Impacts and Economic Valuation" held in Monaco in October 2017.

Table 1
Overview of economic valuation estimates from reefs in select Pacific Basin coral reef ecosystems (c.f. NOAA Coral Reef Information System).

Economic valuation of select Pacific Basin coral reef ecosystems			
	Reef and/or lagoon area (km^2)	Affected population	Economic valuation (millions USD)
American Samoa	296	55,519	11
Hawaii, USA	11,057	1,428,557	455
Marshall Islands	11,670	53,158	–
Palau	1,661	20,918	–
Ryukyu Archipelago, Japan	4,642	1,550,161	–
Total:	29,326	3,108,313	466

Hawaii, United States

The coral reefs of the Hawaiian Islands are comprised of atolls, fringing reefs, and barrier reefs with approximately 50 stony coral species in the archipelago (Friedlander et al., 2004). Ocean acidification observations have been well-documented in the Hawaiian Islands, and are therefore useful for studying the impacts of ocean acidification on coral reefs (Fig. 2). These reef systems support an important regional tourism economy, and even provide existence and non-use benefits beyond Hawaiian waters (Cesar et al., 2002). The Hawaiian Islands are unique in that certain reefs have experienced intense bleaching events with delayed recovery, while others have shown to be resilient to anthropogenic impacts (Bahr et al., 2015). The combination of temperature and ocean acidification-induced bleaching events are the dominant factors harming coral reefs around Hawaii (Lane et al., 2013). Coastal stressors also influence Hawaiian near-shore reefs. For instance, anthropogenic nutrient loading and salinity variability from submarine groundwater discharge (SGD) have shown to

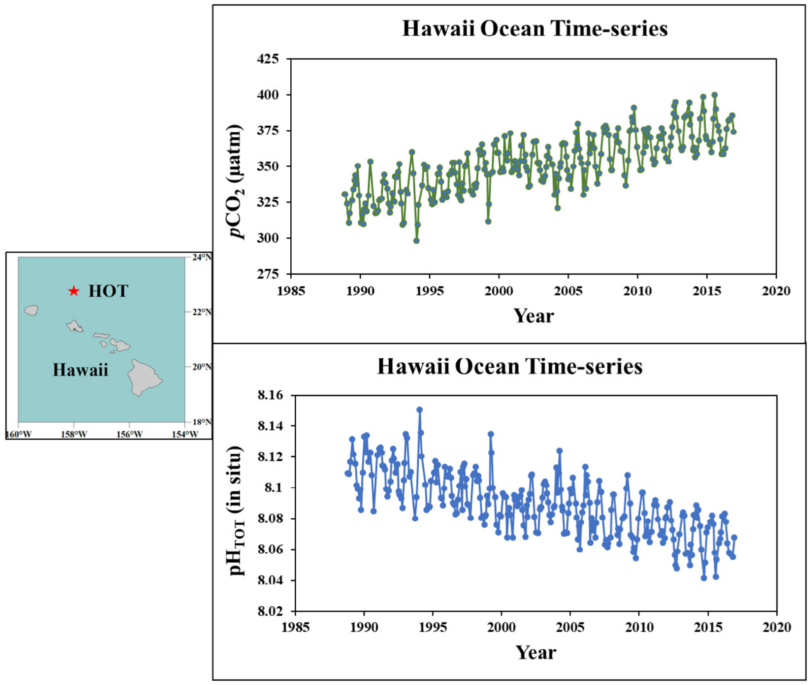

Fig. 2. Surface pCO_2 and pH measurements from the Hawaii Ocean Time-series station over three decades (Richard Feely, NOAA and Marine Lebrec, IAEA, unpublished data).

reduce coral growth and limit survivorship in the otherwise oligotrophic North Pacific Subtropical Gyre (Swarzenski et al., 2017; Richardson et al., 2017; Lubarsky et al., 2018).

While it is well-documented that coral reefs around Hawaii are experiencing stress resulting from global climate change and local drivers such as increased agriculture, overfishing, urbanization, among others, certain Hawaiian reef systems have shown resilience from these stressors. Kaneohe Bay contains a coral reef that has recovered from major disturbances, including reduced pH and eutrophication, serving as an example for future recovery and adaptation strategies to coral reefs experiencing similar pressures (Bahr et al., 2015).

Enforcing management and conservation strategies will become increasingly important for the local tourism economy of Hawaii. Following the "Business as Usual" greenhouse gas scenario, approximately 10.6 billion USD could be lost from Hawaiian recreational services between 2000 and 2100 (Lane et al., 2013).

Marshall Islands

The Marshall Islands exhibit 300 species of corals that are located in over 11,000 km^2 of reef area (Goldberg et al., 2008). The remote location and relatively small size of these islands make them particularly vulnerable to sea-level rise and coral bleaching, compounding other major conservation concerns in this area, such as coastal pollution and marine debris (Oberle et al., 2017; Storlazzi et al., 2018). While ocean acidification impacts on coral reef ecosystems in the Marshall Islands are not currently posing noticeable threats to corals on the national scale, many reefs are facing localized threats, including destructive fishing practices, runoff from land-based sources, and outbreaks of Crown-of-Thorns sea stars (Burke et al., 2011).

A World Resources Institute reef assessment identified that the Marshall Islands economies exhibit among the highest reef dependence in the world based on the following six indicators: reef-associated population, reef fisheries employment, nutritional dependence on fish and seafood, reef-associated export value, reef tourism, and shoreline protection from reefs (Burke et al., 2011). Evidently, as ocean acidification impacts increase globally, the Marshall Islands may experience more extreme socio-economic impacts due to its strong reliance on coral reefs.

Ryukyu Archipelago, Japan

The Ryukyu Archipelago of Japan extends from 24°N to 31°N, and includes several island groups (Okinawa Islands, Daito Islands, Osumi Islands, Yaeyama Archipelago, Miyako Archipelago, Amami Archipelago, and Tokara Archipelago), all of which are primarily comprised of fringing reefs. Although the Ryukyu Archipelago is located at a higher latitude than the other case studies presented in this paper, the set of islands are characterized by their high coral species diversity, with over 360 coral species documented in the archipelago (Veron, 1992). The Kuroshio current transports warm water from tropical to temperate latitudes, resulting in the Ryukyu Islands being among the richest centers of endemism in the world's coral reefs (Roberts et al., 2002).

Similar to other marine ecosystems, the coral reefs of the Ryukyu Archipelago experience perturbations from both natural phenomena as well as anthropogenic stressors. Strong typhoons are prevalent in the region, and can cause damage to reefs from increased wave action and high sedimentation rates from land. In 1998, anomalously high water temperatures were documented along the coast of Japan, following the strongest El Niño event on record. These extreme conditions led to more than 90% of corals bleaching in reefs around the Okinawa Islands, with the most susceptible reef systems experiencing a maximum of 79% mortality (Loya et al., 2001). Other environmental stressors to reefs in the Ryuku Archipelago include Crown-of-Thorns sea star outbreaks and eutrophication from terrestrial runoff. Volcanic CO_2 seeps along the Pacific coast of Japan provide insight on localized effects of high CO_2 in this region, providing a natural laboratory for how coral reefs are likely to respond to future ocean acidification conditions (Inoue et al., 2013; Agostini et al., 2018; Hirano et al., 2019).

As one of the most visited archipelagoes in the East China Sea, the economic revenue from tourism in the Ryukyu Islands

is increasing, with over 4.7 billion USD gained in 2014 solely from tourism, in comparison to the 3 million gained in 1972 (Okinawa Prefecture, 2016). The proliferation in tourism and overcrowding comes at an environmental cost, with obvious signs of degradation of coral reefs and other ecosystems become more frequent.

Palau

With an estimated 425 coral species, Palau has the most diverse coral fauna in Micronesia (Golbuu et al., 2005). The coral reef ecosystems surrounding Palau are smaller and therefore more vulnerable to ocean waves and currents. As typhoons and other extreme weather events become more prevalent in the tropical Pacific Ocean as an indirect result of climate change, coral reef cover has decreased in less protected and shallower environments. In 2013, a typhoon damaged between 60 and 90% of coral reefs in Palau, and shifts in trophic dynamics of certain reefs were documented in alignment with the decrease in coral survivorship (Gouezo et al., 2015).

The status and impacts of ocean acidification in Palau's reef systems are of interest in understanding high tolerances and adaptive responses in corals to low pH environments. The pH in Palau's Nikko Bay is consistent with levels predicted in 2100, yet the bay has high coral cover and diversity. The adaptation of this reef is likely a result of the high residence time in the bay, which limits circulation of coral larvae, allowing selection for traits resistant to low-pH conditions (Golbuu et al., 2016). Monitoring in low-pH sites like Nikko Bay will be increasingly valuable as ocean acidification impacts become more apparent in this Small Island Developing State (SIDS).

Coral reefs provide important services to local tourism businesses. Studies find that 86% of tourists visit Palau to dive and snorkel on coral reefs. Additionally, 40% of employment is generated from tourism, and tourism contributes to approximately 75% of economic growth (Perrottet and Garcia, 2016). Palau experienced a 3.3% decrease in their GDP following an extreme coral bleaching event in 1997–1998, further emphasizing the reliance on healthy reefs for Palau's national economy (Golbuu et al., 2005).

American Samoa

The American Samoan reefs are comprised of approximately 200 species of coral in fringing reef and atoll ecosystems. The National Marine Sanctuary of American Samoa includes six protected areas, covering 13,170 square kilometers of nearshore coral reef and offshore open ocean waters across the American Samoan archipelago. NOAA established the sanctuary in 1986 to protect a small, 0.65 km^2 coral reef ecosystem within Fagatele Bay, and the protected area was expanded in 2012 to include additional islands. While the conservation of reefs in American Samoa is critical, these ecosystems are highly vulnerable to large-scale events such as hurricanes and storms, bleaching events, and Crown-of-Thorns outbreaks.

Localized adaptation to extreme temperature and highly variable pH values in American Samoa from corals has been documented. For example, a back reef in the island of Ofu experiences diurnal fluctuations of pH values ranging between 8.0 and 8.2, and high mean temperatures. Sites such as this could be used in better understanding environmental thresholds to corals in anticipation for future conditions (Koweek et al., 2015). Ocean acidification monitoring efforts have not been widely established in American Samoa; studies thus far have primarily focused on monitoring temperature, disease prevalence, pollution, fishing, and herbivory (Schumacher et al., 2018). Quality baseline data followed by long term observations of the carbonate chemistry in reefs around American Samoa will become increasingly important in better understanding thresholds and resistance to low pH environments from corals in this region.

3. Proposed solutions and case studies

All Pacific Basin coral reef ecosystems presented here are facing profound challenges as environmental stressors are placing coral reef health and ecosystem services at risk. To this end, restoration and protection of these complex systems is increasingly becoming indispensable. Three categories of ecological and socio-economic solutions are proposed for the Pacific Basin coral reef ecosystems: adaptation, mitigation, and capacity building. Adaptation solutions focus on building coral reef resilience to environmental stressors, while mitigation solutions directly target reducing atmospheric and oceanic CO_2. Capacity building refers to collecting baseline data, implementing real-time monitoring, and ultimately advancing research at the local level in order to inform policy at the national and international level. These efforts are already being implemented in certain cases, however, documenting their effectiveness has remained a challenge. The actions proposed are key to understanding how ocean acidification is affecting coral reefs, and ultimately how to manage the associated socio-economic vulnerability. Political will, leadership, and commitment are needed to ensure the success of proposed solutions and underlying mechanisms.

Adaptation

Implementing adaptation measures to coral reef ecosystems from ocean acidification and climate change requires national governments to adopt legal tools adapted to each country's political, economic, and environmental circumstances. Regulation should be more preventative and focused on implementation at the local level. Such tools could include encouraging human activities that ensure sustainable development, such as well-regulated tourism and "eco-tourism" ventures, and local fisheries managed under best practices. Residents could be empowered to protect coral reefs through involvement in education programs and partaking in citizen science projects such as reporting on coral reef health. Such efforts can contribute to a baseline understanding of reef conditions, to then inform how these may be changing over time.

Coral reef restoration as a strategy for adapting to ocean acidification and climate change is becoming a priority in many regions. Such efforts include placing artificial reefs in the form of submerged structures to act as new habitats for corals, fish, and invertebrates. From an economic perspective, sites with previously damaged natural reefs can use artificial reefs to increase scuba diving, and therefore tourism revenue (Belhassen et al., 2017). Building resiliency of coral species to extreme environmental conditions is also advancing through selectively breeding individuals with phenotypes able to withstand extreme bleaching events. Scientists at the Hawaii Institute of Marine Biology have been pioneering efforts of introducing "super-corals" to the natural environment through breeding in the laboratory or using genome editing technology in corals. This approach of coral reef restoration has proven to be controversial as it requires changing naturally occurring evolutionary processes; however, the need for corals to adapt to ocean acidification and climate change is paramount if these ecosystems are to survive future predicted conditions (van Oppen et al., 2015).

While Marine Protected Areas (MPAs) cannot protect an ecosystem against global phenomena such as ocean acidification, it can enhance coral reef resilience to changing conditions by carefully monitoring and limiting human activities within the MPA. Due to the shared challenges facing Pacific Basin coral reef ecosystems, a common protected area shared with several islands could encourage regional collaboration, while allowing for comparisons of spatio-temporal environmental impacts across ecosystems. To this end, the 'Micronesia Challenge' was enacted in 2006 to effectively conserve more than 30% of marine

resources by 2020 across six nations, including the Marshall Islands. Assessments of this effort have identified that conservation targets are most likely to be met when response from local management is enforced. Model outputs reveal that only 42% of the reef systems included in the Micronesia Challenge exceed the ecosystem health threshold needed to be considered successfully protected (Houk et al., 2015). MPAs implemented on the national level in the Pacific Basin coral reef ecosystems have proven to be effective in protecting reefs from destructive fishing practices and pollution at the local level. The nation of Palau recently designated 80% of its territory as fully protected, where no extractive activities are allowed (Fig. 3).

Legal mechanisms, such as the expansion or establishment of MPAs, should be accompanied with effective implementation and enforcement of all accompanying laws and regulations. Any penalties should be adapted to local context and sufficiently dissuasive to avert illegal behavior. This could mean incurring additional costs, such as hiring enforcement officers and vessels. Cross-country collaborations in this region could lower costs, such as regional training workshops for enforcement officers and shared high seas monitoring efforts. Locally nominated "sheriffs" could further enhance local buy-in and effectiveness of these regulations, especially if said regulations are designed, implemented, and enforced by local communities.

Mitigation

In order to effectively mitigate impacts of ocean acidification, global and national agreements to reduce carbon dioxide emissions are needed. There are a range of policy levers that can incentivize industries to lower carbon dioxide emissions which can be applied to the Pacific Basin. These solutions branch from global to local mechanisms, which vary in costs and political feasibility. The environmental economics literature puts forward two main market-based instruments to be used to mitigate global greenhouse gas emissions and, hence, ocean warming and acidification:

- Taxation (e.g. carbon tax) or subsidies (e.g. energy efficiency subsidies, subsidies for renewable energy technologies, feed-in tariffs for renewable energy); eliminating fossil fuel subsidies; and
- Emissions Trading Systems (ETS), or Cap-And-Trade (CAT) programs, based on quota allocation.

Among emissions trading systems, the most significant scheme was designed by the EU member states within the framework of the Kyoto Protocol. In addition, energy efficiency and renewable energy certificate trading systems that aim to promote these mechanisms are also available. Tax-or-subsidy-based control mechanisms may cause rigidities between direct producers and end-users and affect the decisions of market agents in a negative way. Still, effective carbon taxes have proven to cause significant reductions in greenhouse gas emissions in several countries in the world. Although the emissions control mechanism based on carbon trading is more compatible with market rationality, one may face serious problems in auditing and monitoring stages. Furthermore, which quota allocation method will be used for trading and how sectoral allocations will be determined are the factors that bear critical importance for the success of the system.

Along with the tools that can be introduced to mitigate global warming and ocean acidification, there is a need to end the existing incentives that are inconsistent with climate targets as well. For instance, continuation of Fossil Fuel Subsidies (FFS) is a threat for the earth's climate. Elimination of FFS is necessary as these subsidies encourage fossil fuel-based energy systems, distort market signals making renewable energy possibly more costly—thus reducing incentives for investment in renewable energy and hindering its development. Besides market-based mechanisms, technological standards and associated restrictions pertaining to fuel oil, energy efficiency and greenhouse gas emissions may also be employed for climate change mitigation. In addition to these, energy performance certificates and green bonds can be cited among other instruments for emissions reduction.

Coral reef ecosystems provide non-extractive benefits, such as recreational, cultural, and aesthetic benefits. Various environmental economic studies calculate household willingness to pay to protect these services, associated with the protection of coral reefs from anthropogenic threats, either through the establishment of MPAs, payments for ecosystem services, or climate change and ocean acidification mitigation. Such surveys could be implemented to calculate the value of protecting Pacific Basin coral reef ecosystems, and the results of these surveys would inform regional cost–benefit analyses to implement the above-mentioned solutions. Finally, Payments for Ecosystem Services (PES) and biodiversity offsets could provide financial incentives to property and business owners in Pacific Islands to enhance their environmental practices, either by subsidizing better practices through PES schemes or by requiring the purchase of offsets to balance carbon emissions or other negative externalities being generated by the business. Certification schemes and identifying responsible businesses in the region could provide an additional financial incentive for businesses to reduce their environmental impact and contribute to regional coral reef conservation.

International goals aimed at reducing greenhouse gas emissions are essential if impacts of ocean acidification are to be mitigated on a global scale. The United Nation's Sustainable Development Goal (SDG) 14.3 is specifically focused on mitigating impacts of ocean acidification. To incentivize groups to take concrete action toward this goal, the United Nations developed a platform for any group to submit "Voluntary Commitments" toward achieving SDG 14.3. As an example of a Voluntary Commitment, Hawaii recently created a statewide partnership comprised of public and private groups as a forum to find market-based solutions implemented to help meet the UN SDG 2030 Agenda, including clean energy use and local food production. There are presently over 40 Voluntary Commitments (https://oceanconference.un.org/coa/OceanAcidification) around the world taking action toward mitigating ocean acidification. Platforms such as the establishment of Voluntary Commitments can be useful for Small Island Developing States, such as those presented in this paper, for forming potential inter-governmental partnerships to combat impacts of ocean acidification on coral reefs.

Capacity Building

To comprehensively identify management and conservation needs within a country, baseline studies and continuous time-series observations on reef ecosystems are critical. Increased funding toward scientific institutions is recommended to inform evidence-based policy. Building capacity in Pacific Basin coral reef ecosystems should also be prioritized; this can be done through various avenues, such as:

- Education and scientific trainings at all levels, which will build an informed community that has the capacity to implements solutions efficiently and effectively, as well as promote stakeholder buy-in of proposed solutions;
- Finance local conservation initiatives for effective protection of ecosystems, which will generate greater ecological resilience and social responsiveness; and
- Promote regional collaborations and networking between developed and developing nations.

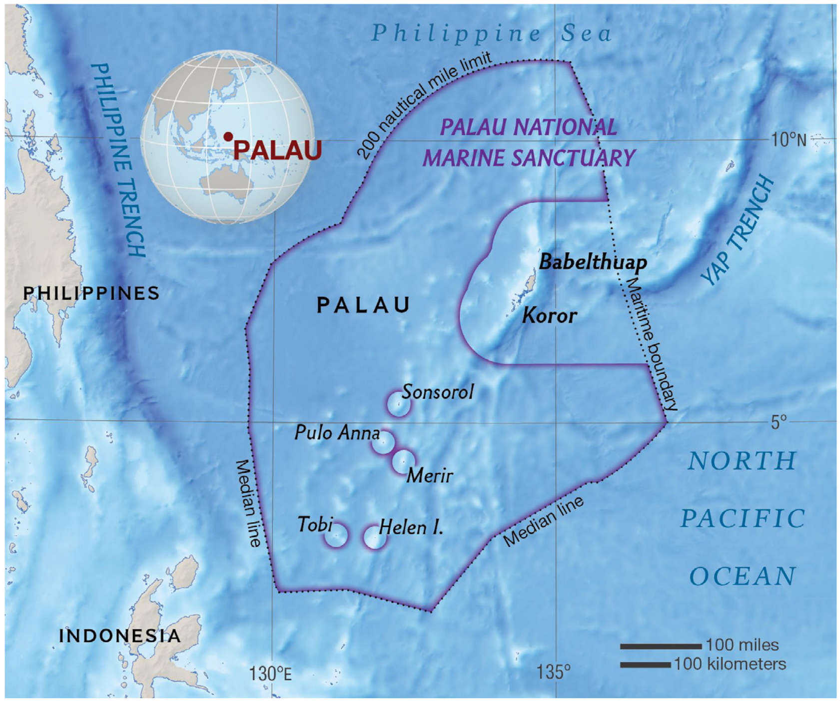

Fig. 3. As one of the largest Marine Protected Areas in the world, the Palau National Marine Sanctuary was established in 2015 to protect ecosystem services provided by coral reefs of this island nation (National Geographic, 2014).

There are several existing international and regional projects aimed at building capacity for local scientists to measure ocean acidification parameters in their countries. For instance, the Ocean Acidification International Coordination Centre (OA-ICC; https://www.iaea.org/services/oa-icc) has supported over 400 scientists from developing countries through training courses, funding travel support for attending international meetings, and providing scientific equipment to measure carbonate chemistry. The Global Ocean Acidification Observing Network (GOA-ON; http://www.goa-on.org/) serves as another international approach to promote international collaboration throughout the scientific community. The GOA-ON is comprised of regional hubs, which are formed through a bottom-up approach by local scientists who are facing similar impacts and challenges to ocean acidification. The newly formed Pacific Islands and Territories Ocean Acidification (PI-TOA) Network will foster collaborations, help in developing adaptation and mitigation solutions, while reflecting differences in science and social capacity between the countries of the regional network. This could lead to higher tolerance for intervention to offset threats in parts of the region where communities rely directly on the reef for sustenance.

In accordance with the United Nation's Sustainable Development Goal 14.3, several capacity building initiatives in the Pacific Islands have been submitted as Voluntary Commitments. The Secretariat of the Pacific Regional Environment Programme (SPREP; https://www.sprep.org/), in collaboration with other intergovernmental and national groups, have formed The Pacific Partnership on Ocean Acidification, which encompassed capacity building and awareness training.

It is essential to encourage funding to projects that directly support local scientists in the Pacific Islands, particularly those focused on identifying the current status and impacts of ocean acidification on coral ecosystems as well as actions needed in response to these threats. As an example, the Hawaii Ocean Time-series (HOT), located 100 km north of Oahu, Hawaii, has been measuring the carbonate chemistry of the surface water for three decades, serving as one of the longest running ocean acidification time series sites (Fig. 2). These measurements have proven to be particularly useful in quantifying and forecasting the status and impacts of ocean acidification both in the Hawaiian Islands as well as on a global scale. Similar long-term monitoring stations in Pacific Basin coral reef ecosystems would be very useful to characterize the local heterogeneity in the carbonate system. Government grants and fellowships can directly finance research and development, whereas regulatory processes, such as cost–benefit analysis, can further support the need for scientific research to understand the tradeoffs involved in undertaking sustainability initiatives. Furthermore, public–private partnerships can facilitate the cross-sectional initiatives that incorporate research, civil society, and the private sector to develop innovative solutions to challenges unique to the region.

Conclusions

Each of the Pacific Basin coral reef ecosystems presented in this paper share similar threats and stressors, while the heterogeneity in reef type, local socio-economic conditions, and governance structures result in very different levels of vulnerability. Key threats include local pollution, overfishing, habitat degradation, overcrowding, and climate change impacts, such as ocean warming and ocean acidification. Socio-economic implications as a result of declined coral reef health will especially target tourism and fisheries industries, but also indirectly in damaged infrastructure from increased erosion.

A recent study predicts that ocean acidification will result in net $CaCO_3$ sediment dissolution by the end of the century, inhibiting shallow corals from building their skeletons (Eyre et al., 2018). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) indicates that up to 90% of warm water coral reefs will disappear once global temperatures exceed a 1.5 °C increase (Hoegh-Guldberg et al., 2018). Although most Pacific Islands are not emitting considerable amounts of greenhouse gases, these nations are at the forefront of climate-change impacts. The root cause of ocean acidification and climate change is well known; restoring coral health is now a matter of implementing new regulations and incentives to reduce greenhouse gas emissions globally. Until such actions are taken, adaptation and conservation

measures must be prioritized to preserve reefs and the ecosystem services they provide. Promoting ocean literacy through, for example, public involvement in local conservation efforts, is key in pushing individuals to make environmentally aware decisions. In order to achieve the various solutions proposed, a strong scientific foundation of these reef ecosystems is essential.

Acknowledgments

Foremost, the authors are deeply saddened by the unexpected passing of Ruth on October 25, 2018. Ruth was an exceptional scientist and pioneer in the field of coral reef biology who worked tirelessly on a 'super coral' that would be better poised against the damaging effects of climate-change, such as ocean acidification and ocean warming. Her life and work is a testament to what can be achieved through scientific innovation and infectious optimism. This work was supported in part by the IAEA Environment Laboratories and the U.S. Department of State through the Junior Professional Officer program (ML). The IAEA is grateful for the support provided to its Environment Laboratories by the Government of the Principality of Monaco. PWS thanks Ms Theresa Fregoso (USGS — Santa Cruz, CA USA) for graphics assistance.

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